Materials Research Proceedings 41 (2024) 1696-1704 https://doi.org/10.21741/9781644903131-188

Flexible self-pierce riveting and clinching with a single joining system using the same unified joining tools

UHE Benedikt[1,a*], SCHÜTZELT Franziska[2,b], DROSSEL Welf-Guntram[2,c] and MESCHUT Gerson[1,d]

[1] Paderborn University, Laboratory for Material and Joining Technology (LWF), Pohlweg 47-49, 33098 Paderborn, Germany

[2] Fraunhofer Institute for Machine Tools and Forming Technology IWU, Nöthnitzer Straße 44, 01187 Dresden, Germany

[a] benedikt.uhe@lwf.upb.de, [b] franziska.schuetzelt@iwu.fraunhofer.de, [c] welf-guntram.drossel@iwu.fraunhofer.de, [d] gerson.meschut@lwf.upb.de

Keywords: Joining, Self-Pierce Riveting, Clinching, Sensitivity Analysis, Unified Tool, Sheet Metal

Abstract. Self-pierce riveting and clinching are well-established joining techniques in car body manufacturing. For these two techniques C-frames with drives, which are mounted on industrial robots, are used to realise the joining process. Punch, die and blank holder, which build the joining tools, are characteristic for the mentioned techniques. Even though the joining tools of self-pierce riveting and clinching are similar, joining with the same unified tools is not implemented in car body manufacturing until now. Within this paper, the challenges and requirements of joining with unified joining tools are described. At the beginning of the examination, reference joints are produced experimentally with conventional joining tools. After that, unified joining tools are elaborated, using numerical simulation. At the end, the feasibility of the approach is demonstrated by experimental joining tests with the newly elaborated joining tools.

Introduction

The mechanical joining technologies *clinching* and *self-pierce riveting* are commonly used joining methods in the sheet metal industry. Both joining methods are suitable for joining two or more joining parts with different thicknesses and tensile strengths, as is used e. g. for joining in composite construction in the automotive industry. There is a recommended joining parts arrangement depending on the joining process. The tool geometry of the punch and the die are different between these two mechanical joining technologies [1].

When changing from clinching to self-pierce riveting, the tool must also be changed. Time and workers are required for the *tool change*, which is problematic for maintaining short cycle times. Apart from this more storage space is required for the two tools, flexibility is decreased and maintenance costs are incurred for both. As the joints are not joined using their preferred joining arrangement, there is a risk of insufficient formation of interlock and neck thickness. In the year 2003, following experimental investigations, Breckweg and Wößner presented a system-side implementation in their patent [2] with a focus on rivet feed and punch drive in order to alternately set clinching and self-pierce riveting joints with a uniform tool.

This paper combines the clinching and self-pierce riveting tools into a *single tool for clinching and self-pierce riveting* without tool change using the same punch-die combination. Optimized tool geometries are derived with the aid of modern numerical simulation methods and sensitivity analysis, similar procedure to the optimization of semi-tubular riveting tools in [3] and the design of tool geometries for clinching, see [4].

Materials Research Proceedings 41 (2024) 1696-1704 https://doi.org/10.21741/9781644903131-188

Self-pierce Riveting and Clinching

For the self-pierce riveting (SPR), the sheets are clamped between the blank holder and the die. Then the rivet is pressed into the sheets by the punch. After piercing the punch-sided sheet the rivet flares so that an interlock is generated within the die-sided sheet, see Figure 1. At the process end, the punch and the blank holder are run back.

The interlock and the minimum die-sided material thickness are the most important characteristic joint parameters [5]. A sufficient interlock has to be created to ensure an appropriate joint strength. The minimum die-sided material thickness indicates that the die-sided sheet is still intact after joining. This is required to prevent corrosion. Through the closed die side of the joint no media can get into the joint [6]. The geometrical and mechanical properties of the rivet as well as the contour of the die are varied to customise the process configuration to the joining task. The main parameters of the die are the depth and the width. The rivet geometry is mainly characterised by the nominal diameter, the nominal length and the hole contour [7]. With the self-pierce riveting sheet materials up to a tensile strength of 2000 MPa can be joined reliably. The preferred joining arrangement with self-pierce riveting is high strength to low strength and thin to thick [8].

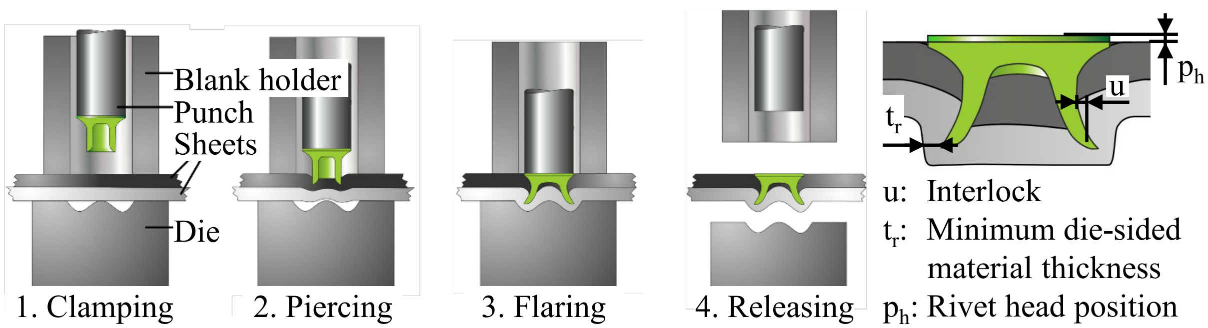


Figure 1: Characteristics of the self-pierce riveting process and the riveted joint

In opposite to the self-pierce riveting, no auxiliary element is required for *clinching*. To create a joint only a punch and die are needed. As for the self-pierce riveting the sheets are clamped by a blank holder. In the context of this paper, only rigid dies are of interest. The process stages of the clinching process are shown in Figure 2. At the beginning, the sheets are clamped between the die and the blank holder. Then the sheet material is formed into the die by the punch. The material of the die-sided sheet is formed into the ring channel so that the material of the punch-sided sheet can generate an interlock within the die-sided sheet. At the end, the tool is released [9].

The main characteristic joint parameters are the interlock, the neck thickness and the bottom thickness. A minimum bottom thickness has to be ensured for the same reason as for the self-pierce riveting. The interlock and the neck thickness define the joint strength. Through clinching sheet material with a tensile strength up to 600 MPa can be joined. The preferred joining arrangement with clinching is high strength to low strength and thick to thin [10]. The adaptation of the process parameters to the properties of the sheet to be joined can be achieved through adjusting the geometries of the punch and the die. Main parameters to do so are the punch diameter, the contour of the punch, which can include a tip or can be designed conically, and the diameter and the width of the die [11]. For self-pierce riveting as well as for clinching joining systems consisting of a C-frame a drive and a control unit are used [8].

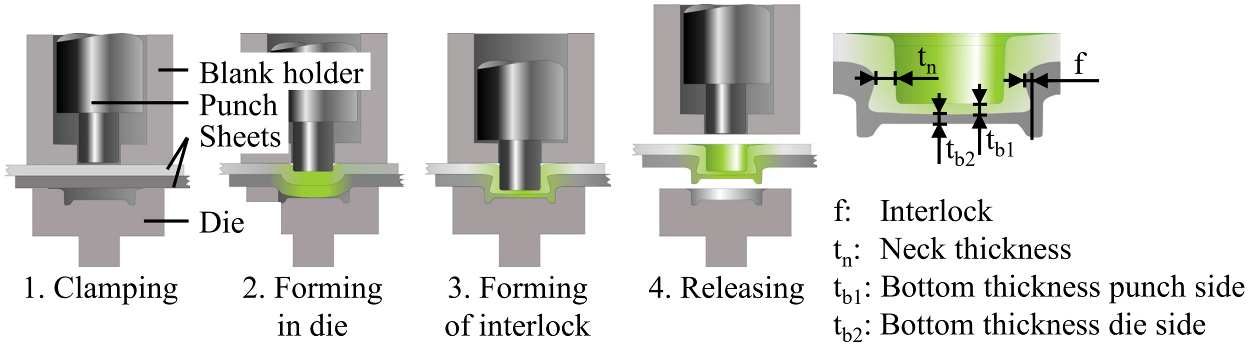


Figure 2: Characteristics of the clinching process and the clinched joint

Selection of Rivets and Clinching Tools

The experimental part of the investigation focusses on a joining task, which comprises the steel CR340LA and the aluminium alloy EN AW-5182. An overview of the properties of the examined sheets is given in Table 1. The yield strength in Table 1 was determined experimentally through compression tests. The selected material combination is joined from two sides, resulting in two cases with different requirements for the joining process and the used joining tools. It has to be recognised that preferred joining directions of self-pierce riveting and clinching are disregarded. Through that, a wide range of possible applications of the tools to be developed can be covered. This is especially relevant for the clinching process, where small changes in the sheet material properties have already a great influence on the interlock as well as on the neck and bottom thicknesses.

Table 1: Properties of the examined sheets

Material	Thickness	Yield strength
CR340LA	1.5 mm	Ø 473 MPa*
EN AW-5182	2.0 mm	Ø 108 MPa*

* determined in compression tests
number of experimental tests n = 5

For the selection of suitable rivets and dies for self-pierce riveting on the one hand and appropriate clinching tools on the other hand, experimental joining tests are conducted. To this, a joining system of type TOX® TZ-VSN 08.413026 (TOX® PRESSOTECHNIK GmbH & Co. KG, Germany) is used. The system consists of a C-frame, a servo-electrical drive and a control unit. It allows riveting and clinching with a single joining system by using different tool holders.

Rivets and dies from Tucker® (STANLEY Engineered Fastening Tucker GmbH, Germany) are used for self-pierce riveting. For clinching tools from TOX® (TOX® PRESSOTECHNIK GmbH & Co. KG, Germany) are used. The produced joints with the selected rivets, dies and clinching tools are shown in Table 2. The C-rivet is common for joining tasks with mild steel and aluminium. The selected rivets for the two different kinds of joints only differ in their length. The rivet material 38B2 is quenched and tempered to a hardness of 480 ± 30 HV10, which corresponds to the hardness class H4 from [8].

Materials Research Proceedings 41 (2024) 1696-1704 https://doi.org/10.21741/9781644903131-188

Table 2: Properties of the selected rivets, dies and clinching tools

	Joining task			
	EN AW-5182 + CR340LA		CR340LA + EN AW-5182	
SPR	**Rivet** Type: C Length: 5.5 mm Material: 38B2 H4 Coating: Almac®	**Die** Type: T057 Width: 9.5 mm Depth: 2.0 mm	**Rivet** Type: C Length: 5.0 mm Material: 38B2 H4 Coating: Almac®	**Die** Type: T008 Width: 9.0 mm Depth: 2.0 mm
Clinching	**Punch** Type: AB60100 Diameter: 6.0 mm Shank: cylindrical End face: without tip	**Die** Type: BE8016 Width: 8.0 mm Depth: 1.6 mm	**Punch** Type: AC56100 Diameter: 5.6 mm Shank: conical End face: without tip	**Die** Type: BE8010 Width: 8.0 mm Depth: 1.0 mm

The punch for the self-pierce riveting has a diameter of 7.5 mm. The produced joints are shown in the next section in the context of the validation of the numerical models. For the comparison of simulation and experiment, the stiffness of the joining system is eliminated by adjusting the experimentally measured force-displacement-curves. The SPR dies and the clinching tools are used as reference for the development of the same unified tools for both joining techniques. Based on the produced joints, numerical models, which are necessary to elaborate unified joining tool geometries, are created as described in the next section.

Numerical simulation

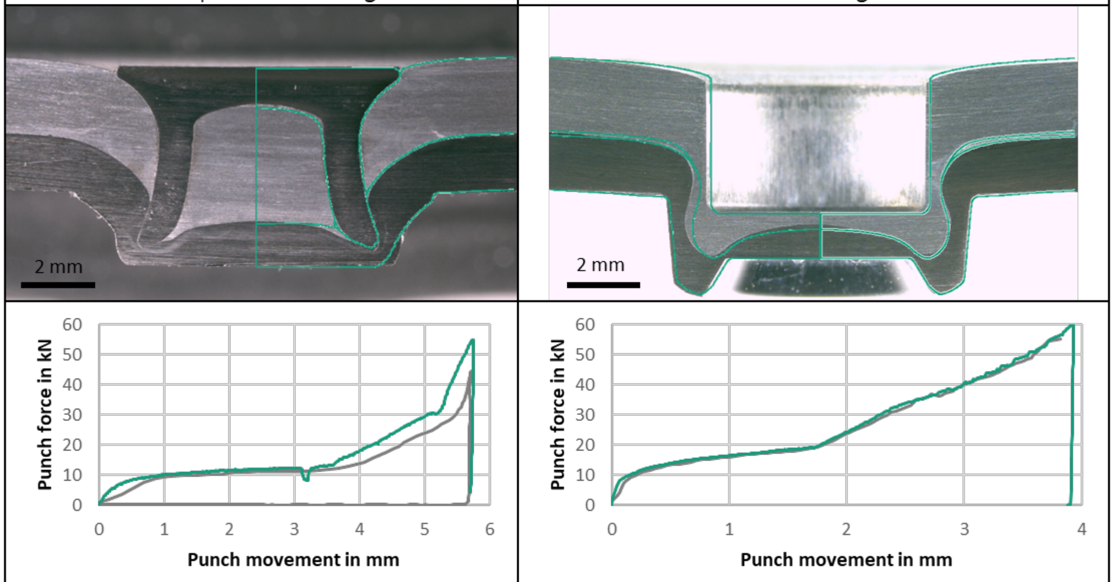
The numerical simulation is performed using the commercial FEA software DEFORM v13.0 from SFTC with the integrated Newton-Raphson iteration for implicit calculation. Joining parts and rivet are cross-linked with elastic-plastic material behavior, tools (e. g. punch) are assumed rigid. The numerical simulation is limited to the joining device consisting of the punch, blank holder and die. The elasticity of the joining pliers is not taken into account in the calculation. Analogous to the tools used in the experiment for the two different kinds of joints as shown in the previous chapter, rotationally symmetric 2D models are used as an established method [3, 4] instead of computationally intensive 3D processes. Compared to the edge of the simulated sheet metal finer meshes are generated in areas of high deformation like neck areas and interlock. The geometric separation criterion is used for simulating SPR. The data of the flow curve stored for the simulation was determined experimentally in compression tests. The coefficient of friction was based on own experience from previous parameter studies and data from the literature. The minimal bottom thickness t_b generated during the experiments was used as stopping criterion in the numerical simulation.

The numerical model was validated by comparing it with experimental results, confirming its accurate reproduction of the joint behavior without errors. The green colored contour is the result of the simulation in the following figure. As shown in Figure 3, the load-stroke curves and the characteristic geometrical values were compared between the experiment (gray) and simulation (green) of the two exemplified kinds of joints. The experimental cross-section and calculated contour are almost identical. Small deviations can be observed in the SPR joint of the second joint, particularly within the rivet. It is difficult to achieve a good agreement at this point of the punched-out material. In the simulation, a constant value is assumed as the friction coefficient over the entire sheet metal surface, while the coating inside the rivet may be slightly different, resulting in different behavior due to factors such as different roughness.

Materials Research Proceedings 41 (2024) 1696-1704 https://doi.org/10.21741/9781644903131-188

EN AW-5182 t = 2,0 mm in CR340LA t = 1,5 mm

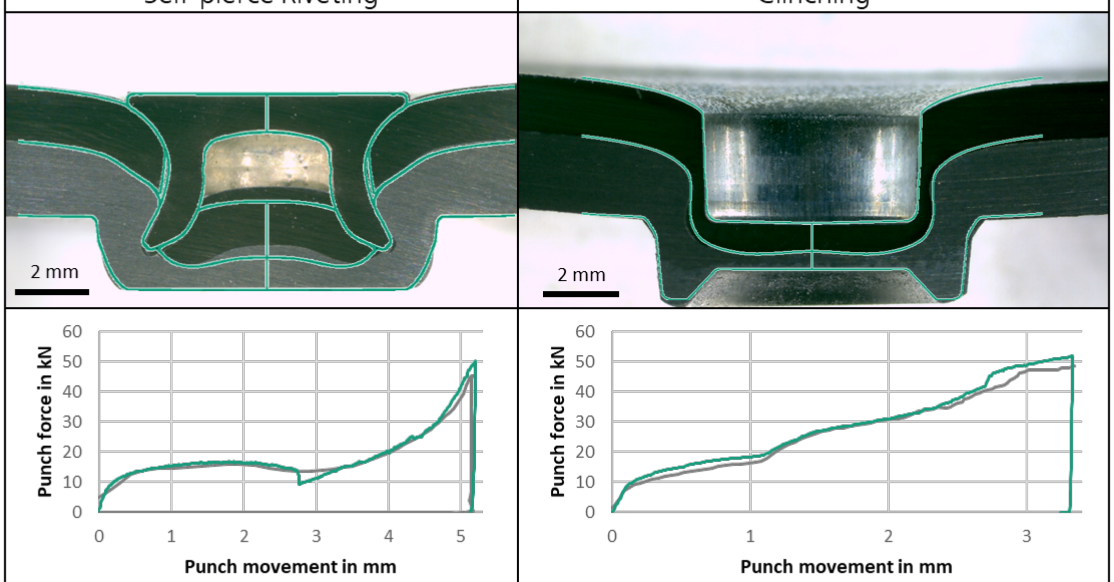
Self-pierce Riveting | Clinching



	$u_{1,2}$ in mm	t_r in mm	F in kN		f in mm	t_n in mm	F in kN
Exp.	0.32 | 0.35	0.40	44.9	Exp.	0.22 | 0.26	0.36 | 0.43	55.4
Sim.	0.31	0.47	55.0	Sim.	0.22	0.30	60.0

CR340LA t = 1,5 mm in EN AW-5182 t = 2,0 mm

Self-pierce Riveting | Clinching



	$u_{1,2}$ in mm	t_r in mm	F in kN		f in mm	t_n in mm	F in kN
Exp.	0.55 | 0.43	0.65	45.3	Exp.	0.21 | 0.13	0.30 | 0.36	48.8
Sim.	0.45	0.64	50.1	Sim.	0.01	0.40	52.0

Figure 3: Comparison of experimental cross-section and simulated contour and resulting characteristic geometrical values of the SPR joint (left) and clinch joint (right) for the two different kinds of joints

The characteristic geometric values generated by the simulation are also almost identical to those of the experiments. This leads to the conclusion that the numerical simulation has high

Materials Research Proceedings 41 (2024) 1696-1704 https://doi.org/10.21741/9781644903131-188

predictive power and accuracy and can be used in the following sensitivity analysis instead of costly experiments.

Sensitivity Analysis

With the help of numerical simulation, a sensitivity analysis is used to evaluate the dependencies between the input and output parameters. The numerical simulation models for the sensitivity analysis are set up parametrically. The Design of Experiments (DoE) of the parameters to be varied is carried out using the commercial statistical software OptiSlang v7.4 from Dynardo. Parameters to be varied are e. g. die diameter from 8 mm to 10 mm, die depth from 1 mm to 2 mm and punch diameter from 5.5 mm to 6.4 mm. For the sensitivity analysis each analyzed joint is tested by 70 numerical simulations. Once the simulation complete, the characteristic geometrical values are measured automatically using the generated joint contour based on a Python script in DEFORM and prepared for the import into the statistical software OptiSlang. This approach has already proven its worth in numerous research projects like [3, 4, 12].

For each investigated joint, a metamodel was computed. Figure 4 shows the resulting metamodel of the sensitivity analysis of clinching joint 1 (EN AW-5182 $t = 2$ mm in CR340LA $t = 1.5$ mm) to show the influence of die depth and die diameter on neck thickness and interlock. Thanks to the combination of multiple metamodels, as done in projects like [4], [12], and [13], an optimal parameter range for the constructive design of the unified tool can be identified for the investigated joints.

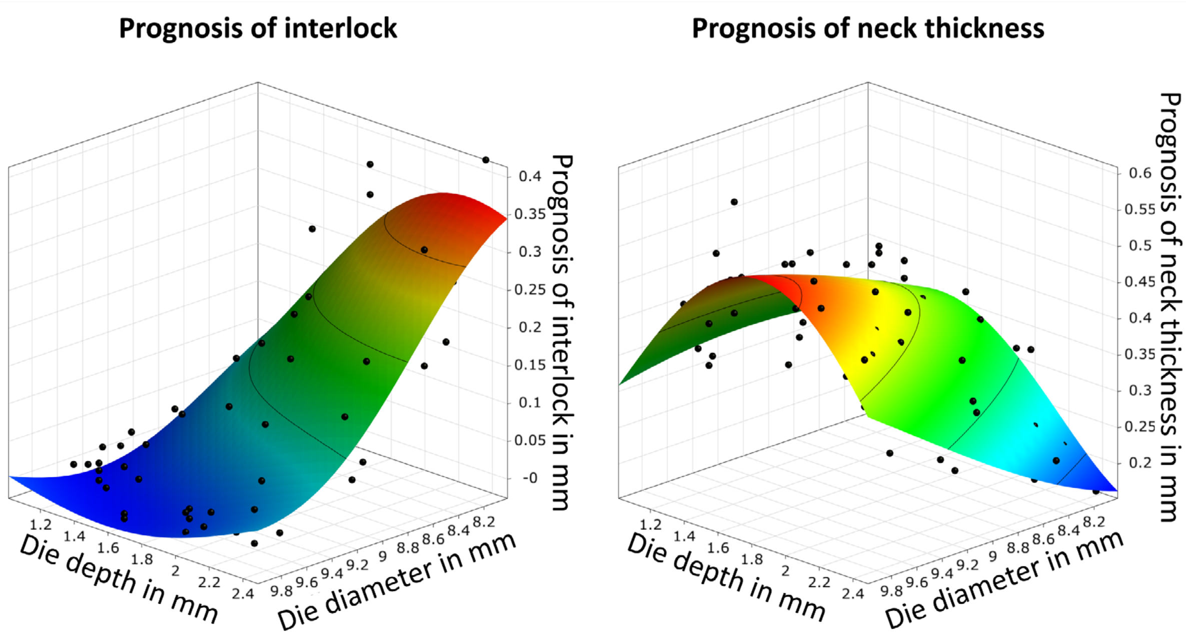


Figure 4: Resulting metamodel to show the influence of die parameters on interlock (left) and neck thickness (right)

By reducing the information from the 3D metamodels like Figure 4 to a response surface 2D plot, for example, the influence of die depth and die diameter can be compared across all different joints that have been investigated in this paper, as shown in Figure 5. It can be observed that an increase in die diameter leads to a reduced interlock. In contrast, it can be noted that a deeper die (see blue and gray lines in the plot) results in a greater formation of interlock. Additionally, it can be noted that a die depth of 1.1 mm is not suitable for the investigated joints as it does not result in sufficient interlock formation.

The Coefficient of Prognosis (CoP) of the interlock in the investigated joints is, with approximately 70 % to 90 %, lower than the CoP of the neck thickness, which is around 85 % to

95 %. Since the interlock is formed relatively late in the joining process, it is correspondingly harder to predict. This should be taken into account when comparing the results of the metamodel analysis and the real experiment. On the other hand, the change in neck thickness occurs continuously with the start of the punch entry into the material and can therefore be predicted better.

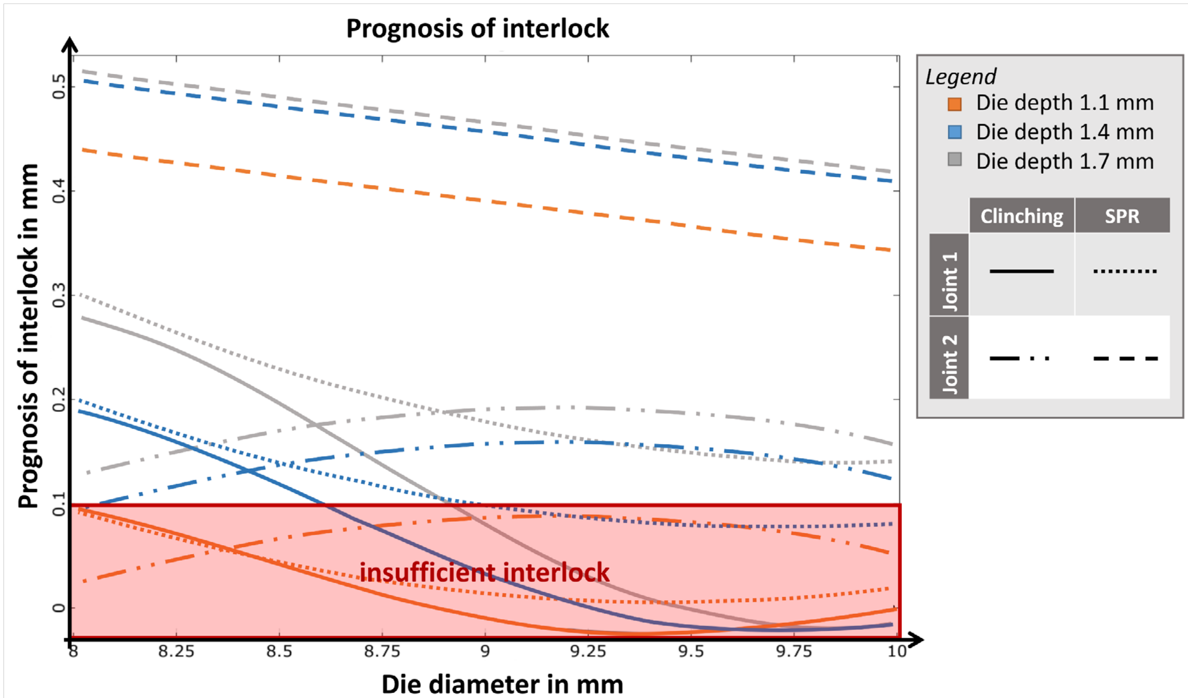


Figure 5: Overview of the influence of die depth and die diameter on the formation of interlock

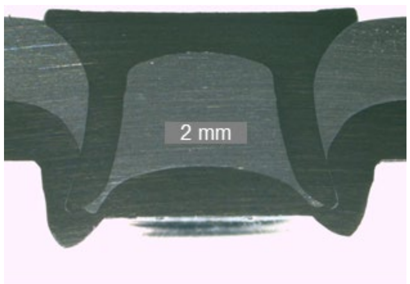
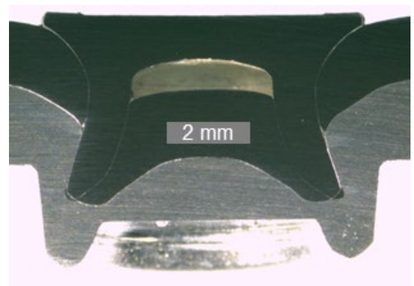
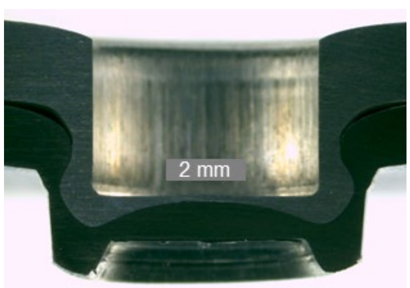
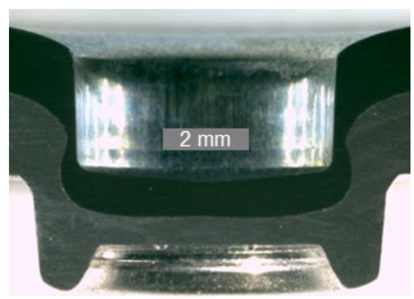
However, for designing the unified tools, it is not only crucial to consider the influence of die parameters on the formation of interlocks. The influence on neck thickness and bottom thickness must also be considered in the tool design. The metamodels demonstrate a mutual influence between interlock and neck thickness, which must be taken into account when selecting the optimal tool parameters for the unified tool. An increase in interlock always leads to a decrease in neck thickness in clinch joints. In addition to the die parameters, the punch parameters like the radius of the punch edge primarily influence the neck thickness of clinch joints. The sensitivity analysis also shows that the choice of punch diameter does not have a negative impact on the formation of the SPR joint, despite having a smaller punch diameter than the rivet diameter.

Furthermore, it is also clearly visible that joint 2 corresponds to the preferred joining direction of SPR. A significant formation of interlocks can be observed in the SPR joint, while the clinch joint shows relatively small interlocks, not exceeding 0.2 mm, despite increasing die depth. On the other hand, it can also be said that even without considering the preferred arrangement of the joining partners, joints can still be generated with optimized tool parameters.

Materials Research Proceedings 41 (2024) 1696-1704 https://doi.org/10.21741/9781644903131-188

Experimental verification of the approach

After the simulation-based development of the unified joining tools, the numerical results are verified by experimental tests. This is done for the considered joining task as explained above. With both joints and both joining techniques, a clinching die of type BE8014 is used. The diameter of the punch is 6.0 mm. The results of the experimental joining tests are shown in Figure 6. It can be seen that the lower punch diameter provokes a small indentation on the rivet head. As the joining force with the same rivet as before remains, the load in the rivet head is increased due to the lower contact area between punch and rivet.

	Joining task			
	Joint 1: EN AW-5182 + CR340LA		Joint 2: CR340LA + EN AW-5182	
SPR	u = 0.32 mm t_r = 0.25 mm		u = 0.33 mm t_r = 0.41 mm	
Clinching	u = 0.33 mm f = 0.54 mm t_{b1} = 0.17 mm t_{b2} = 0.10 mm		u = 0.16 mm f = 0.25 mm t_{b1} = 0.81 mm t_{b2} = 0.65 mm	

Punch: Newly manufactured with a diameter of 6.0 mm

Die: Conventional clinching die BE8014 with a width of 8.0 mm and a depth of 1.4 mm

Figure 6: Cross-sections of the joints produced with the unified joining tools

As the diameter of clinching punches is always lower than the diameter of 7.5 mm of the riveting punch, an optical impairment has to be accepted when unified joining tools are used for self-pierce riveting. As the rivet head always represented an optical impairment of the sheet surface, this effect can be tolerated. An impact on the mechanically properties of the rivet and the joint is not expectable, because of the very low deformation in an area that is not relevant for the joint strength. The clinching dies are convenient for self-pierce riveting as well. The clinched joint does also meet all quality criteria. Thus, it can be stated that both material combinations can be joined by self-pierce riveting and clinching with unified joining tools.

Summary and Outlook

Within this paper, an approach for the unification of the joining tools for self-pierce riveting and clinching was presented. The challenges and requirements of joining with the same unified tools for both joining techniques were described. The feasibility of the approach was demonstrated for two different joining tasks. The chosen material combination consists of steel and aluminium. First, suitable rivets and joining tools were selected and reference joints were produced experimentally. Then, numerical models were created and unified joining tools were elaborated based on a sensitivity analysis. Finally, the unified joining tools were used for the chosen joining task and it could be shown that that self-pierce riveting and clinching with unified joining tools is feasible.

Based on the results presented in this paper, the authors plan to develop unified joining tools for ten different material combinations in total. When the unified joining tools are manufactured, a comparison of experimentally produced joints will be conducted. After that, a comparison of the joint strength of joints produced with conventional and with unified tools is planned.

Acknowledgements
The results presented are taken from IGF research project 22047 BG of the European Research Association for Sheet Metal Working (EFB), which has been funded by the German Federation of Industrial Research Associations (AiF) under the program for promotion of industrial research (IGF) run by the Federal Ministry for Economic Affairs and Climate Action (BMWK) based on a decision by the German Bundestag.

References

[1] G. Meschut, V. Janzen, T. Olfermann: Innovative and Highly Productive Joining Technologies for Multi-Material Lightweight Car Body Structures. Journal of Materials Engineering and Performance, 23 (2014) p. 1515-1523. https://doi.org/10.1007/s11665-014-0962-3
[2] A. Breckweg, J. Wößner: Vorrichtung zum Verbinden von plattenförmigen Bauteilen mit variabler Fügetechnik am 15.07.2003 (DE10332124B4). Deutsches Patent- und Markenamt.
[3] W.-G. Drossel, M. Israel: Sensitivitätsanalyse und Robustheitsbewertung beim mechanischen Fügen. EFB-Forschungsbericht, No. 376, 2013. EFB, Hannover.
[4] T. Falk, T. Kropp, W.-G. Drossel: Clinching with divided punch to prevent critical neck thicknesses. Materials Research Proceedings Series, Volume 28, p. 1059–1066, 2023. 1st ed. Millersville: Materials Research Forum LLC. https://doi.org/10.21741/9781644902479-116
[5] D. Li, I. Chrysanthou, G. Patel, G. Williams: Self-piercing riveting - A review, Int. J. Adv. Manuf. Technol. 92 (2017) p. 1777–1824. https://doi.org/10.1007/s00170-017-0156-x
[6] H. Ang: An Overview of Self-pierce riveting Process with Focus on Joint Failures, Corrosion Issues and Optimisation Techniques, Chin. J. Mech. Eng. 34 (2021) 2. https://doi.org/10.1186/s10033-020-00526-3
[7] K. Mori, Y. Abe: A review on mechanical joining of aluminium and high strength steel sheets by plastic deformation, Int. J. Lightweight Mater. Manuf 1 (2018) p. 1–11. https://doi.org/10.1016/j.ijlmm.2018.02.002
[8] Technical Bulletin DVS 3410, Self-Pierce Riveting - Overview, DVS Media: Düsseldorf, Germany, 2019.
[9] M. Eshtayeh, M. Hrairi, A. Mohiuddin: Clinching process for joining dissimilar materials: state of the art, Int. J. Adv. Manuf. Technol. 82 (2016), p. 179-195. https://doi.org/10.1007/s00170-015-7363-0
[10] DVS-EFB Merkblatt 3420: Clinchen-Überblick, 2021, DVS Media, Düsseldorf.
[11] B. Shi, Y. Wang, S. Liu, H. Tian: Design method of the parameters of tools for clinching technology, 455-456 (2012) p. 1491-1496. https://doi.org/10.4028/scientific5/AMR.455-456.1491
[12] T. Falk, W.-G. Drossel: Methodische Flexibilitätssteigerung beim Halbhohlstanznieten. EFB-Forschungsbericht, No. 513, 2019. EFB, Hannover.
[13] T. Falk, T. Kropp, M. Jäckel: FEM simulation for the development of data-based process models in mechanical joining technology. 10th International Seminar & Conference on Advances in Resistance Welding & Mechanical Joining 2018. Esslingen, Germany, 12-14th September 2018.